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The Calculated and Measured Resistance for Splices between Conductors in a MICE Superconducting Coil

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1 March 2009*

Abstract

The resistance of superconducting joints within MICE coils is an important issue particularly for the coupling coils. The MICE tracker solenoids have only two superconducting joints in the three spectrometer set (end coil 1, the center coil and end coil 2). The AFC magnets may have only a single joint within the coil. The coupling coils may have as many as fifteen joints within the coil, due to relatively short piece lengths of the superconductor. LBNL and ICST looked at three types of coil joints. They are; 1) cold fusion butt joints, 2) side-by-side lap joints, and 3) up-down lap joints. A theoretical calculation of the joint resistance was done at LBNL and checked by ICST. After looking at the theoretical resistance of the three types of joints, it was decided that the cold welded butt joint was not an attractive alternative for joints within a MICE superconducting magnet coil. Side-by-side and up-down lap joints were fabricated at ICST using two types of soft solder between the conductors. These conductor joints were tested at LBNL at liquid helium temperatures over a range of magnetic fields. The joint resistance was compared with the theoretical calculations. Measurements of splice strength were also made at 300 K and 77 K.

TABLE OF CONTENTS

	Page
Abstract	1.
Theoretical Calculations of MICE Coil Joint Resistance	2.
Fabrication of Superconductor Joints at ICST	11.
Conductor Joint Resistance Measurement Technique	13.
Measured Joint Resistance Compared with Calculated Joint Resistance	16.
Measurements of the Joint Breaking Strength	19.
Some Concluding Comments	25.
Acknowledgements	26.
References	26.

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Theoretical Calculations of MICE Coil Joint Resistance

The MICE magnets [1] may have joints within the coils. Since the MICE magnets are continuously powered using one or more 300 A power supplies, the conductor joints in the coil do not have to be persistent. Since the MICE magnets have potted coils (either wet wound or epoxy impregnated) and the magnets are cooled using small coolers, there is a need for the joint resistance to be low in order to prevent heat buildup within the magnet when it is carrying current. As a result, the maximum allowable joint resistance has be set to 10 nΩ. In the highest current coils in MICE (the tracker solenoid coils), the heat produced in the joints at 275 A would be about 0.76 mW. The tracker solenoids have ten joints [2]. These joints are in liquid helium. In the tracker solenoids the total joint heating is expected to be less than 10 mW. The coupling coils, which have a maximum current of 213 A, will have joint heating of around 0.45 mW per joint. Up to fifteen joints may be buried within the potted coil in the coupling magnets [3], [4]. All of the joints in the coupling magnet must produce less than 10 mW of heating.

Two types of coil joints have been considered for the MICE superconducting coils. The joint considered include: 1) cold welded butt joints between conductors, and 2) soldered lap joints between the conductors across their flat faces. Hybrid joints that were a combination of butt and soldered lap joints were briefly considered, it was felt that hybrid conductor joints didn't offer the advantages of either type of joint while having the disadvantages of both types of joints. Figure 1 illustrates a butt joint and a soldered lap joint of length L.

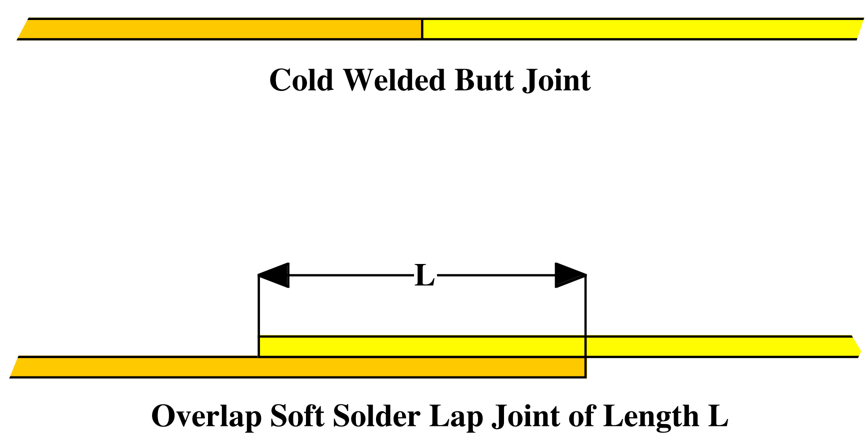


Figure 1. An Illustration of a Cold Welded Butt Joint and an Overlapped Soft Solder Joint

Cold welded butts joints are attractive because they are stronger than the conductor itself and they can be wound into a coil without the loss of a turn. The problem with this type of joint is can the joint resistance be low enough for use in a MICE magnet. An expression for the resistance of a butt joins is given as follows;

$$R_j = \frac{\rho_j L_j}{A_{cj}} \frac{(r+1)}{r} \qquad \text{-1-}$$

where R_j is the resistance of the joint; ρ_j is the electrical resistivity of the material in the butt welded region of the joint; L_j is the length of the fused region within the joint; r is the copper to superconductor ratio for the conductor that is cold welded together; and A_{cj} is the cross-sectional area of the conductor joint. The cross-section area of the joint is the same as the cross-section area of the conductor that is fused together to make the joint. For a conductor similar to the MICE conductor, the cross-section area of the joint can be calculated suing the following expression;

$$A_{cj} = tw - 4{R_{Cu}}^2 + \pi {R_{Cu}}^2 \qquad \text{-1a-}$$

where w is the width of the conductor; t is the thickness of the conductor; and R_{Cu} is the radius of the copper corner of the rectangular conductor. Figure 2 below shows the basic dimensions for a typical conductor that is being used to wind the MICE tracker and coupling magnets.

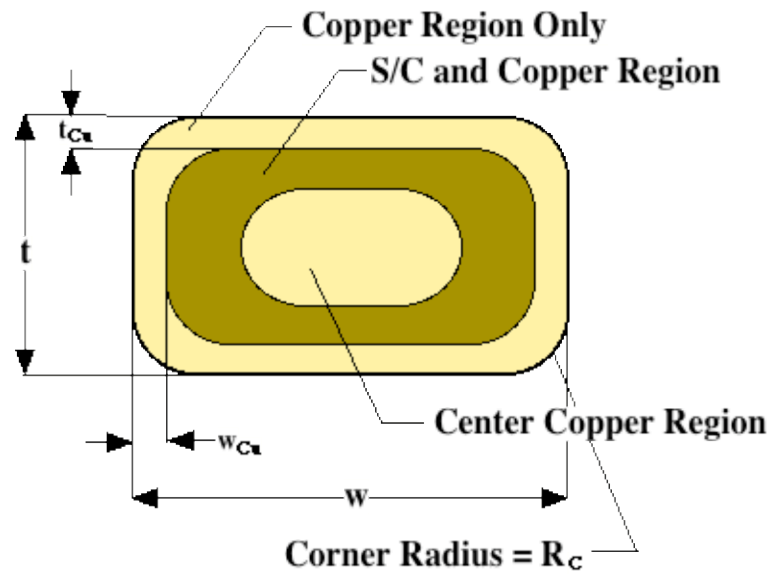
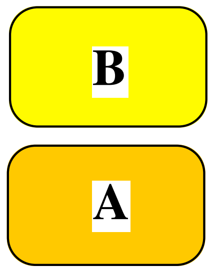


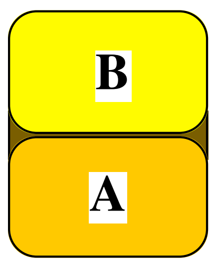
Figure 2. The Dimensions used in the Calculation Equations for the Resistance of Joints in a Typical Superconductor within a Coil

There two predictability problems with a cold welded butt joint. They are: 1) The joint resistivity ρ_j is unknown. 2) The fused length of the joint L_j is also not known. If the joint is fabricated from a conductor with large niobium filaments and the cross-section was polished before cold welding, the joint may be superconducting at low field, but one can't always depend on the joint being superconducting. Conductor joints within MICE coils may be at field as high as 6 T. At 6 T, the cold welded butt joint will certainly be normal. One can estimate the resistance of a cold welded butt joint for MICE magnets using a conductor that has bare dimensions t = 0.95 mm by w = 1.6 mm with R_{Cu} = 0.2 mm. If $\rho_j = 1.6 \times 10^{-9}$ Ωm (the copper RRR = 10), and the weld zone thickness L_j = 100 µm and $A_{cj} = 1.5 \times 10^{-6}$ m^2, the joint resistance will be about 106 nΩ, which is an order of magnitude too high for the MICE magnets. The calculated joint resistance agrees reasonably well with some measurements made some years ago on a butt joint made by cold welding two conductors with a cross-section area of 6 square millimeters. The measured butt joint had a resistance was about 25 nΩ [5].

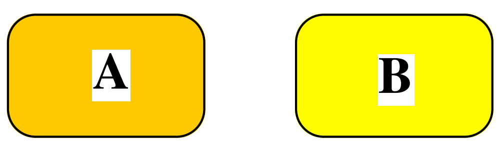
Since the cold welded butt joints have a resistance that is too high for MICE magnets, one must look at lap joints where a low temperature soft solder is used to bond the two conductors together. Figure 3 illustrates two types of lap joints that may be used in a MICE magnet. These are the up-down lap joint and the side-by-side joint. The up-down joints are suitable, if they can be tucked into the ground plane insulation at the ends of a coil, because there will be no turns will be lost in a coil layer. It is better to use a side-by-side joint in magnet coils with a large number of turns per layer, because less superconductor will be thrown away in the winding process. However, side-by-side joints will have a higher resistance and a turn will be lost in the coil layer where the joint is located. In both joint cases, it is assumed that the conductor is wound in the easy direction. (The conductor is bent in the short direction during winding.)



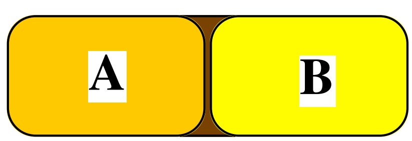
Stripped Conductor before making the Up-down Lap Joint



Soldered Conductor after making the Up-Down Lap Joint



Stripped Conductor before making the Side-by-side Lap Joint



Soldered Conductor after making the Side-by-side Lap Joint

Figure 3. Up-down and Side-by-side Soft-soldered Lap Joints Made with a Rectangular Conductor that is Similar to the Conductor used in the MICE Tracker and Coupling Magnets (The two conductors are shown after the insulation has been removed and then after the conductors have been soldered together.)

Figure 3 illustrates how up-down lap joints and side-by-side lap joints are made. Before soldering the conductor together, the sections of the conductor to be soldered together must be stripped of their insulation. After the joint has been soldered, it is reinsulated using Kapton or a varnish that is painted on the bare joint. The key to making good quality joints is controlling the temperature and compressing the joint together so that the solder layer thickness is minimized. Voids in the solder and sections of solder filled with flux should be avoided.

One can calculate the joint resistance for up-down lap joints and side-by-side lap joints by using the following expression;

$$R_j = R_{Cu} + R_{Sol} \qquad \text{-2-}$$

where R_j is the joint resistance; R_{Cu} is the resistance of the copper between the superconductor and the solder; and R_{sol} is the resistance of the solder in the joint.

The copper resistance in the joint R_{Cu} can be calculated using the following expressions;

$$R_{Cu} = \frac{2\rho_{Cu} t_{Cu}}{L(w - 2R_c)}, \text{ for up-down joints and} \qquad \text{-3a-}$$

$$R_{Cu} = \frac{2\rho_{Cu} w_{Cu}}{L(t - 2R_c)}, \text{ for side-by-side joints.} \qquad \text{-3b-}$$

L is the length of the lap joint; t_{Cu} is the copper thickness in the t direction; w_{Cu} is the copper thickness in the w direction; t is the rectangular conductor thickness; w is the rectangular conductor width; and R_c is the radius of the corner of the conductor. (See Figure 2 for a definition of t, w, t_{Cu}, w_{Cu}, and R_c. See Figure 1 for a definition of L.) ρ_{Cu} is the resistivity of the copper in the conductor that is between the superconductor and the solder.

The resistance of the solder R_{sol} is given by the following approximate expressions;

$$\frac{1}{R_{sol}} \approx \frac{L(w - 2R_c)}{\rho_{sol} t_{sol}} + \frac{2LR_c}{\rho_{sol}(R_c + t_{sol})}, \text{ for up-down joints and} \qquad \text{-4a-}$$

$$\frac{1}{R_{sol}} \approx \frac{L(t - 2R_c)}{\rho_{sol} t_{sol}} + \frac{2LR_c}{\rho_{sol}(R_c + t_{sol})}, \text{ for side-by-side joints.} \qquad \text{-4b-}$$

L is the joint length; t_{sol} is the solder thickness at the flats of the conductor; R_c is the corner radius; and ρ_{sol} is the resistivity of the solder.

A simplified version of Equations, 3, and 4 that ignores the rounded corners can be derived. (This assumes that there is no solder in the rounded corners.) The resulting equation should be a worst-case for calculating the joint resistance. In reality, there will always be some solder in the corner region. The simplified equation takes the following form;

$$R_j = \frac{2\rho_{Cu} t_{Cu}}{L(w - 2R_c)} + \frac{\rho_{sol} t_{sol}}{L(w - 2R_c)}, \text{ for up down joints and} \qquad \text{-5-}$$

$$R_j = \frac{2\rho_{Cu} w_{Cu}}{L(t-2R_c)} + \frac{\rho_{sol} t_{sol}}{L(t-2R_c)}, \text{ side by side joints} \qquad \text{-6-}$$

When the rectangular conductor has no rounded corners ($R_c = 0$), the joint resistance should be a minimum for a given joint length L. The equations for the joint resistance R_j takes the following forms for up-down joints and side-by-side joints;

$$R_j = \frac{2\rho_{Cu} t_{Cu}}{Lw} + \frac{\rho_{sol} t_{sol}}{Lw}, \text{ for up down joints and} \qquad \text{-7-}$$

$$R_j = \frac{2\rho_{Cu} w_{Cu}}{Lt} + \frac{\rho_{sol} t_{sol}}{Lt}. \text{ for side-by-side joints.} \qquad \text{-8-}$$

When two round conductors of radius R_C are soldered together, Equations 2, takes the following form;

$$R_j \approx \frac{2\rho_{Cu} t_{Cu}}{\pi L R_c} + 0.5\frac{\rho_{sol}(R_c + t_{sol})}{L R_c} \qquad \text{-9-}$$

In this case t_{Cu} is the average thickness of the copper between the superconductor and the surface of the conductor.

The resistivity of the copper is dependent on the copper RRR (the resistance at 273 K divided by the resistance at 4 K) and the magnetic field seen by the copper. The resistivty of the solder is dependent on magnetic field. An approximate expression for the resistivity of the copper is given by the following expression;

$$\rho_{Cu} = \frac{1.55x10^{-8} + \frac{1.55x10^{-8}}{RRR}}{RRR} + 4.77x10^{-11}B \qquad \text{-10-}$$

where RRR is the residual resistance ratio for the copper and B is the magnetic field the copper sees. The expression given above is valid at 4 K over a range of RRR from 3 to 1000 and a range of magnetic inductions from 0 to ~8 T. Above 8 T, the copper begins to saturate and the magneto-resistance doesn't change very much. The magneto resistance of the solder seems to be small but very close to linear from no field to 10 T.

Table 1 presents the resistivity of the copper and a lead-tin (60Pb-40Sn) soft solder at 4.2 K as a function of magnetic induction seen by the copper and the soft solder [6], [7]. From Table 1 and the equations above, it is clear that at low RRR, the copper becomes a more important part of the joint resistance. At an RRR = 70 (the MICE tracker and coupling coil conductor), the joint resistance is dominated by the solder in the joint. Therefore it is very important that the thickness of the solder between the conductor flats be minimized. This require very good control of the heating of the conductor, so that the solder become fully liquid. Getting the conductor too hot for too long a period of time will result in a reduction of the superconductor critical current. The joint resistance is in fact be strongly influenced by the quality of the soldering.

Table 1. The Resisrivity of 60Sn-40Pb Solder and Copper as a Function of RRR and Magnetic Induction

B (T)	ρ_{sol} (Ω-m)	ρ_{Cu} (Ω-m)		
		RRR = 7	**RRR = 70**	**RRR = 300**
0	5.40x10^{-9}	2.53x10^{-9}	2.25x10^{-10}	5.18x10^{-11}
2	5.50x10^{-9}	2.62x10^{-9}	3.20x10^{-10}	1.47x10^{-10}
4	5.59x10^{-9}	2.72x10^{-9}	4.15x10^{-10}	2.42x10^{-10}
6	5.69x10^{-9}	2.81x10^{-9}	5.11x10^{-10}	3.37x10^{-10}
8	5.78x10^{-9}	2.88x10^{-9}	5.85x10^{-10}	4.11x10^{-10}
10	5.88x10^{-9}	2.90x10^{-9}	6.06x10^{-10}	4.42x10^{-10}

Figure 4 shows a cross-section of the MICE conductor that is used in the MICE tracker solenoids and the MICE coupling solenoids. The bare conductor width is 1.6 mm; the bare conductor thickness is 0.95 mm. The MICE conductor insulation thickness is about 25 microns. From Figure 4, one can see that t_{Cu} = ~150 microns. The average value of w_{Cu} is ~200 microns. It should be pointed out that the copper inside the layer of superconducting filament does not contribute to the resistance of the joint between the conductors. Most conductors with a copper to superconductor ratio of 4 will be made in way that is similar to what is shown in Figure 4. Figure 4 also shows that the rounded corners on the MICE conductor have a radius pf about 200 microns as specified in the conductor specification. The cross-section are of the conductor shown in Figure 4 is 1.5 mm^2. The 41-micron diameter superconducting filaments are clearly shown in the conductor cross-section shown below. The filament spacing is 6 to 8 microns.

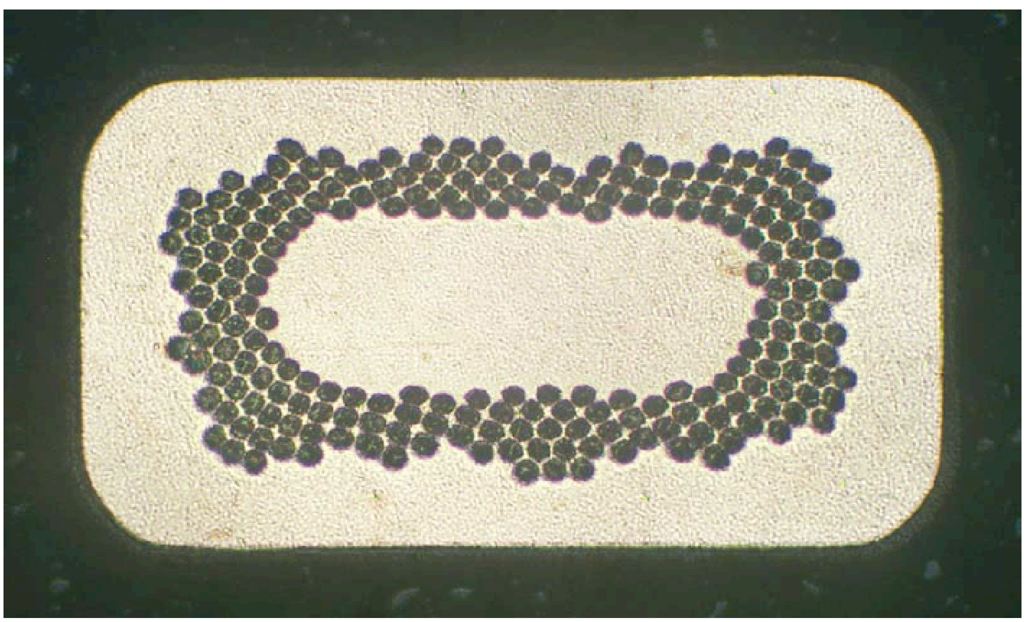


Figure 4. A Cross-section of the Lavata MICE Tracker Magnet and Coupling Magnet Superconductor

Calculations of MICE magnet joint resistance were done for the simplified cases first. The four right hand columns in Table 2 show the resistance of the solder portion of a 1-meter long joint, with 100 microns of solder between the flat surfaces conductor copper. For comparison a joint resistance calculation is done for a joint between equivalent round wires (see Equation 9). (For a cross-section area of 1.5 mm^2, the wire diameter 1.38 mm.), The resistance of the 1-meter long joint using the simplified equations is done for the MICE conductor shown in Figure 4 (Equations 5 and 6) with the MICE conductor and a conductor without rounded corners (equations 7 and 8). The calculation are done for an up-down joint, and a side-by-side joint.

Table 2. The Calculated Joint Resistance for a Joint between Two 1.38 mm Round Wires and between Two MICE Conductors (0.95 x 1.60 mm) with Up-down and Side-by-side Joints for Solder Thicknesses of 100 μm. The simplified calculations were done for a corner radius of 0.2 mm and a corner radius of zero. (Note: The copper RRR = 70, t_{Cu} = 150 μm, w_{Cu} = 200 μm. For the round wire t_{Cu} = 190 μm.)

B (T)	1-meter Long Joint Resistance (nΩ)				
	Round	**Rectangle (up-down)**		**Rectangle (side-by-side)**	
	R_c = 0.69 mm	**R_c = 0.2 mm**	**R_c = 0**	**R_c = 0.2 mm**	**R_c = 0**
0	2.95	0.518	0.389	1.147	0.662
2	3.01	0.555	0.417	1.234	0.713
4	3.08	0.591	0.444	1.320	0.764
6	3.20	0.628	0.472	1.408	0.816
8	3.30	0.659	0.495	1.480	0.854
10	3.32	0.673	0.505	1.514	0.871

From Table 2, it is clear that 1-meter long lap joints have a lower resistance when made with rectangular wire than when made with round wire with the same cross-sectional area. It is useful to point out that resistance calculated using equation is approximate. Equation 9 suggests that the joint resistance is almost independent of the size of the conductor. This is not completely true. The authors suggest that an FEA model be used to accurately calculate the resistance of joints between round wires. For splices between round wires the resistance of the solder appears to be the dominate term, when the copper in the conductor has an RRR = 70.

When the conductor copper has an RRR = 70 in a rectangular conductor, the solder resistance also dominates the splice resistance. Thus reducing the solder thickness in joints for a rectangular conductor will directly affect the joint resistance. The side-by-side joint has about 2.2 times the resistance of an up down joint when MICE conductor is spliced. If the rounded corner radius of the MICE conductor were reduced zero, the side-by-side joint would have about 1.7 times the resistance of the up-down joint. Given that the calculations made for Table 2 are somewhat conservative, one should have no difficulty getting joint resistances well below 10 nΩ using 1-meter long lap joints made with MICE conductor in either orientation. If the effect of the solder in the corners is considered, the actual splice resistance will be between the R_C = 0 and the R_C = 0.2 mm values given in Table 2.

When the data in Table 2 is plotted as shown in Figure 5, one sees that the effect the magnetic field is not very strong. The magneto resistance term is quite strong in the copper up to about 8 T. The magneto resistivity term for the solder is much smaller compared to the base resistivity of the solder. Solder has a lower RRR than the pure metals that make up the solder, so it is expected that the base resistivity (due to defects in the metal) would be much higher than the magneto-resistivity term. Since the conductor splice resistance is dominated by the resistance of the solder, the resistance of the joint in a magnetic field is dominated more by the resistance of the solder than that of the copper. The authors predict that magnetic field won't be an important factor in determining the resistance of splices in MICE magnets.

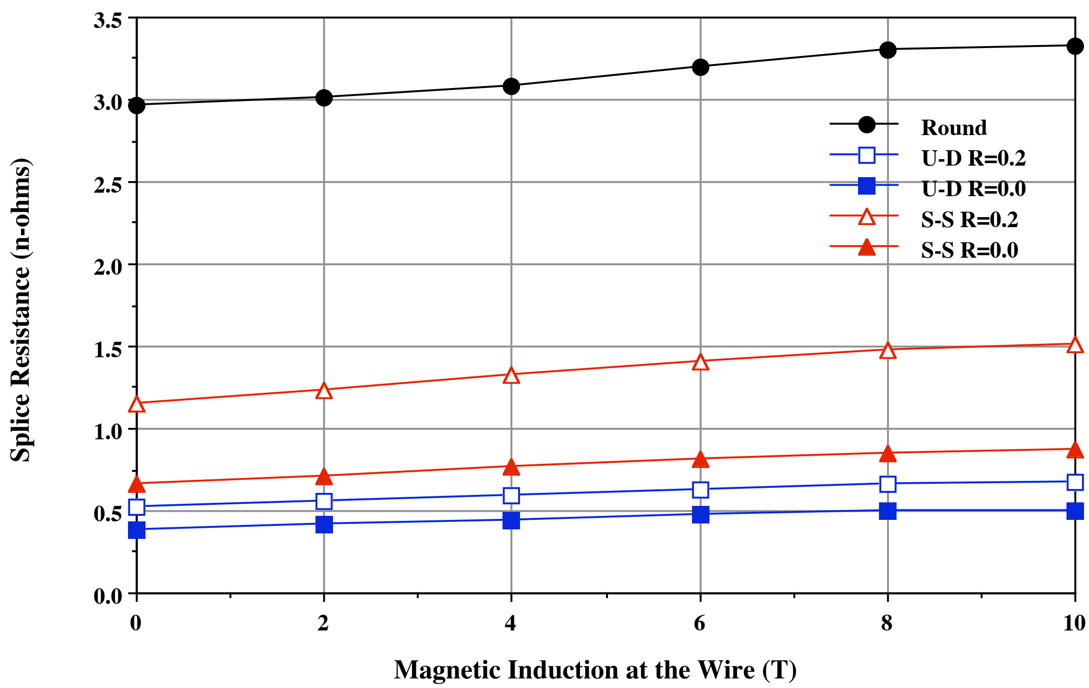


Figure 5. The Calculated Resistance for a 1-meter Long Splice of MICE conductor as a Function of Magnetic Field Up-down joints (open and closed squares) are compared to side-by-side joints (open and closed triangles). Joints made MICE conductor (squares and triangles) are compared with a 1-meter long joint made with a round wire that has the same cross-section area (1.5 mm^2) as the MICE conductor. The effect of the corner size can be compared by comparing the open and closed squares and triangles. The open square and triangle symbols are for conductor with R_C = 0.2 mm. The closed square and triangle symbols are for a MICE conductor with R_C = 0.

When one estimates the effect of the solder at the corners (equations 4a and 4b), one gets a joint resistance between the curves with filled and unfilled symbols in Figure 5. Table 3 and Figure 6 show the calculated resistance for a 1-meter long splice made with MICE conductors (R_c = 0.2 mm) using equations 3a, 3b, 4a, and 4b. The conductors shown in Table 3 and Figure 6 are spliced together with both up-down and side-by-side splices. Figure 6 shows the effect of solder thickness for both the up down and side-by-side splices as a function of magnetic field at the splice and the thickness of the solder joint between the conductors. The cases shown in Figure 6 are cases, in which the 60Sn-40Pb solder is 100 and 200 microns thick between the flat sides of the MICE conductor.

As with the splices as shown in Table 2 and Figure 5, the splices shown in Table 3 and Figure 6 appear to be dominated by the solder resistance and the thickness of the solder joints. From Table 3 and Figure 6, it is hoped that one can estimate the actual thickness of the eutectic sin-lead solder in the joint fabricated by ICST. The measurements of actual joints using solders with 63Sn-37Pb and 96Sn-3.5Ag-0.5Cu are presented later in this report.

Table 3. The Calculated Resistance of 1-meter Long Splices between Two MICE Conductors (0.95 x 1.60 mm) with Up-down Splices and Side-by-side Splices for Solder Thicknesses of 100 µm and 200 µm. (Note: The copper RRR = 70, t_{Cu} = 150 µm, w_{Cu} = 200 µm, and R_C = 0.2 mm as shown in Figure 4.)

B (T)	1-meter Long Joint Resistance (nΩ)			
	Rectangle (up-down)		**Rectangle (side-by-side)**	
	T_{sol} = 100 µm	**T_{sol} = 200 µm**	**T_{sol} = 100 µm**	**T_{sol} = 200 µm**
0	0.461	0.844	0.898	1.487
2	0.490	0.882	0.972	1.572
4	0.516	0.914	1.044	1.654
6	0.539	0.945	1.100	1.721
8	0.567	0.979	1.176	1.806
10	0.580	0.999	1.207	1.848

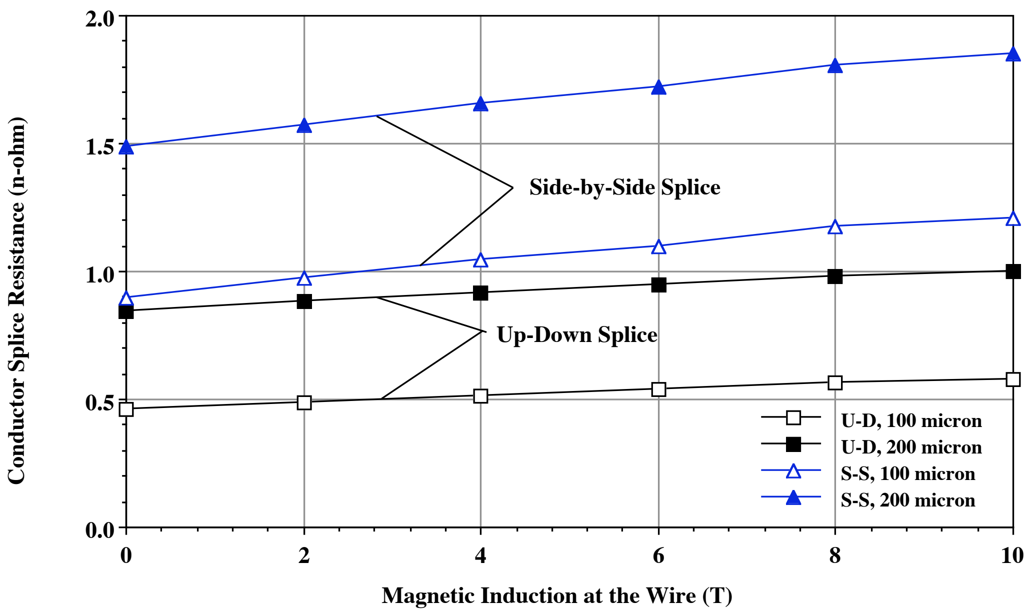


Figure 6. The Calculated Resistance for a 1-meter Long Splice of MICE conductor as a Function of Magnetic Field Up-down joints (open and closed squares) are compared to side-by-side joints (open and closed triangles). The solder in the splices are 100 micron thick (the open symbol) or 200 microns thick (the symbol). The solder used for the calculation is the 60Sn-40Pb solder with the resistivity shown in Table 1.

The splice resistance calculated for Table 3 for 100-micron thick solder is less than the splice resistance calculated in Table 2 for R_C = 0.2 mm with no solder in the corners. The solder thickness used for the calculation in Table 2 was also 100-microns thick. Increasing the solder thickness from 100 microns to 200 microns increases the splice resistance by about 1.72 for an up-down joint. Increasing the solder thickness from 100 microns to 200 microns increases the splice resistance by about 1,53 for a side-by-side joint. The splices used for the calculations in Table 3 and Figure 6 are 1-meter long, as in Table 2 and Figure 5. From the theory it is clear that joint resistance is inversely proportional to the joint length and proportional to the normal material in the joint just as it is with HTS conductors [8]

Fabrication of Superconductor Joints at ICST

A number of splices were fabricated by the people at ICST. For the most part, all of these ICST splices are hand made. The sections of conductor to be joined had the Formvar removed by abrasion with a scraping tool. This tool removed the insulation and about 50 microns of the copper from the conductor. After the insulation was removed, the bare conductor was cleaned using ethyl alcohol. Hemostats were used to hold the conductor pieces together while they are fluxed and soldered using a low temperature soldering iron. The method of splice fabrication is shown in Figure 7. Care was taken to see that the temperature of the conductor was kept below 225 C during the soft soldering process. The time that the conductor was kept above 200 C was typically less than 2 minutes. After the full-length solder joint was made, the joint was scraped removing the excess solder. The finished dimension of the spliced conductor was close to the dimension one would expect for two bare conductors pushed together. For an up-down joint this dimension is expected to be 1.6 by 1.9 mm. For a side-by-side joint this dimension is expected to be about 0.9 by 3.2 mm.

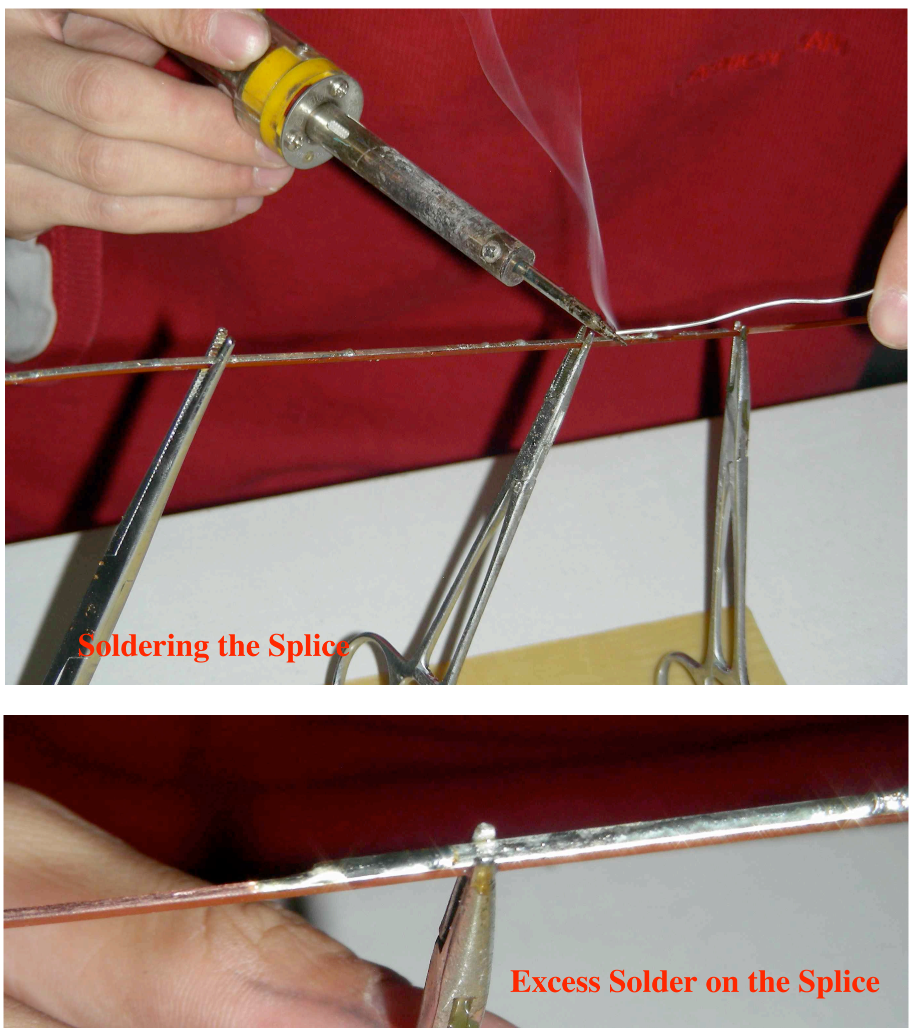


Figure 7. The Fabrication Technique used for the ICST Superconductor Splices tested by LBNL

ICST has made up-down splices, which is the preferred splice if the conductor splice can be made at the ends of the magnet coil. ICST has also made side-by-side splices, which potentially could be used within a magnet coil. If a side by side splice is used, one must lose one full coil turn for each splice made within the magnet. Finished conductor splices of both types are shown in Figure 8. The upper part of Figure 8 is a side-by-side splice. The photo was taken in May 2008. The lower part of Figure 8 is an up down splice fabricated at ICST on 22 May 2008. (See Figure 7 for fabrication photos.) From Figure 8, one can see that the solder between the conductors is reasonably thin ~ 200 microns.

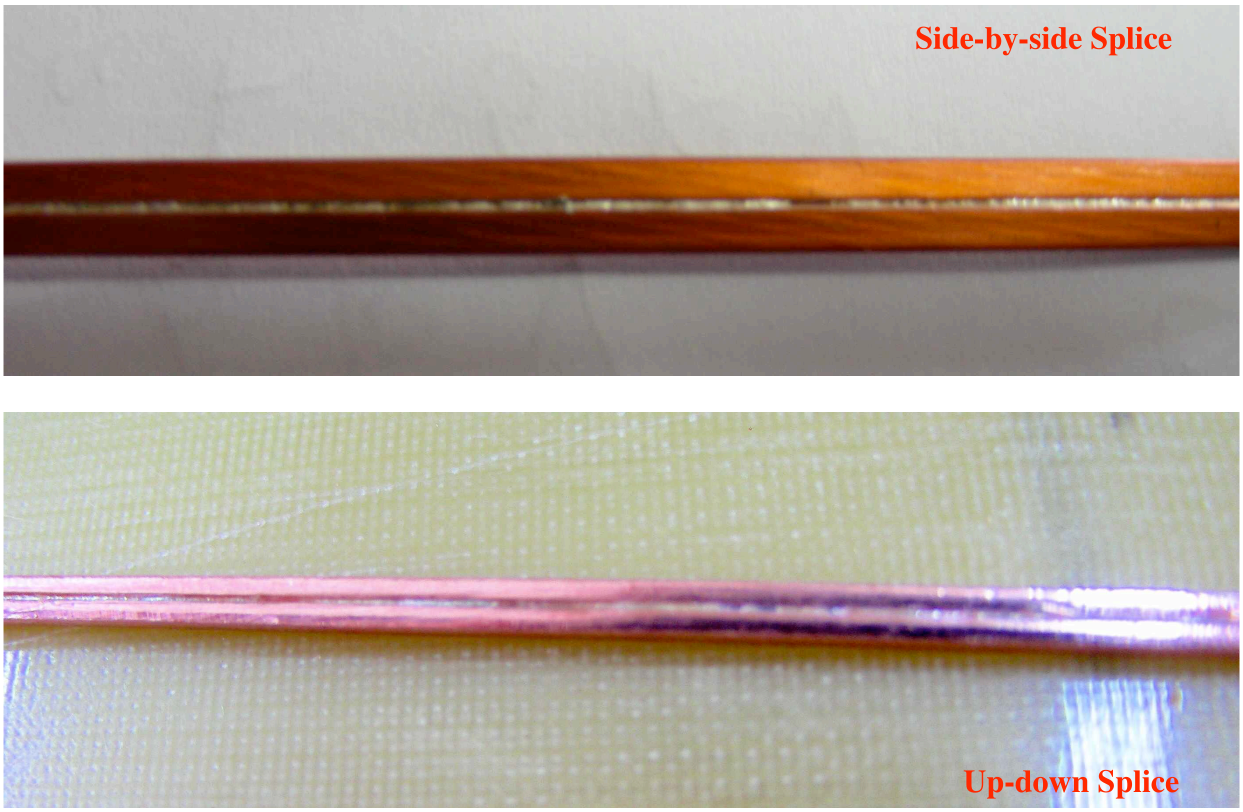


Figure 8. ICST Conductor Splices. (The upper part is a side-by-side splice; the lower part is an up-down splice}

The splices made by ICST for the LBNL joint resistance tests vary in length from about 0.25 m to just over 1.0 m. The solder used in the ICST splices is of two types. The first type of solder is 63Sn-37Pb lead-tin eutectic solder. The second is a lead free solder 96Sn-3.5Ag-0.5Cu. ICST has experience with tin-silver solder on magnet projects because they used the solder on magnets for IHEP in Beijing. There is resistivity data for the tin-lead solder (See Table 1), but we have no resistivity data for the lead free solder. It is hoped that the joint resistance tests at LBNL will permit us to determine the resistivity of the lead free solder. With the splices fabricated by ICST, we can measure the effect of splice length, the effect of the solder, and the effect of the magnetic field on the splice resistance.

The process that ICST used to make the test joints is quite time consuming. It is hoped that the process can be automated somewhat. ICST hopes to reduce the time to fabricate the splices and they hope that the joint quality will be more uniform. The joints shown in Figure 8 appear to be good enough to use in the MICE and MuCOOL magnets.

Conductor Joint Resistance Measurement Technique

Samples of ICST splices were sent to LBNL for measurement. The bore of the 15 T magnet used for the measurement of the joint resistance is relatively small. The maximum sample size is a little over 65 mm. The sample tube used for mounting the samples are made of G-10. The sample tube OD is 50.8 mm (2 inches). The samples were wound on the outside of the sample tube as illustrated in Figure 9.

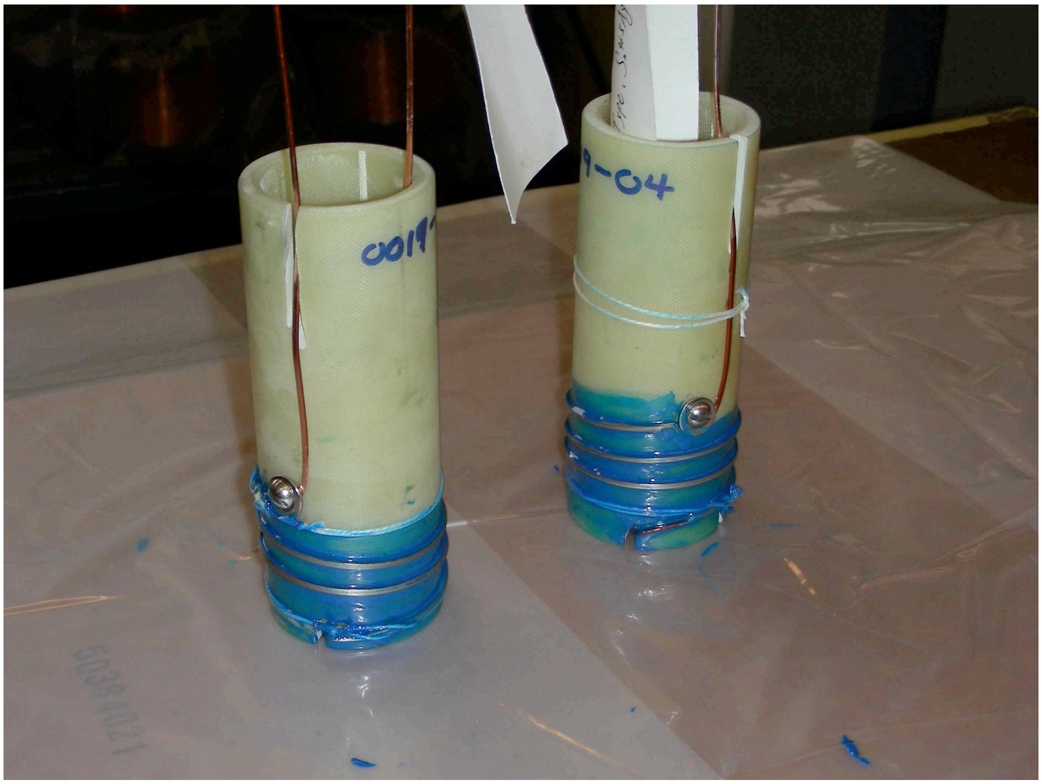


Figure 9. Sample Tubes for Measuring the Resistance of the ICST Conductor Splices

After the samples were wrapped they a glued with Stycast to the G-10 sample tube, they were wired up for measurement. Current leads were attached to the end wires of the sample and four voltage taps were attached to the sample in various places so that the voltage drop could be measured in the sample at various places. A similar technique has been used for measuring the resistance of HTS joints [9]. Figure 10 shows the voltage tap position on the splice samples measured by LBNL. Figure 11 shows the sample holder from the end.

Before going further it should be pointed out that the splice (joint) samples measured at LBNL were subjected to much higher strains than the splices would see when they are wound into any of the coils wound at ICST. The samples at LBNL are bent to a radius of 25 mm. The conductor in the small ICST test coil is bent to a minimum radius of 175 mm. The conductor in the large ICST test coil and the coupling coils is bent to a radius from 750 mm to 855 mm depending on where the conductor is within the coil. As a result of bending of the samples over a small radius, some of the samples show some peeling of the solder near the ends. Comparing the voltage drop across the center regions of the joint as compared to the ends is a measure of the degradation that can occur in a splice that is of small radius.

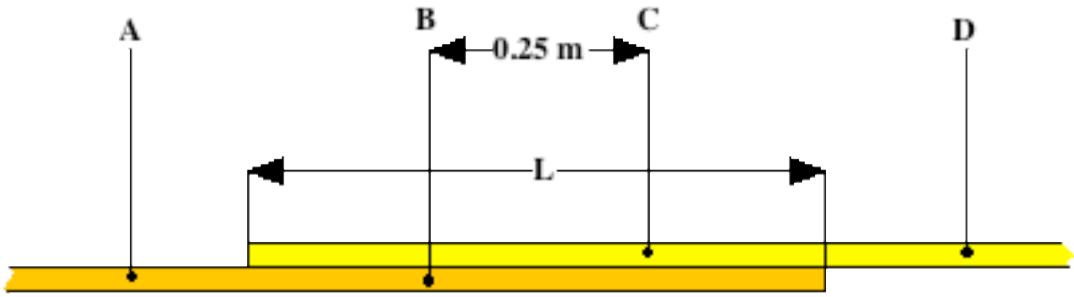


Figure 10. The Voltage Tap Arrangement for the Joint Samples tested at LBNL (The splice length is L. The voltage drop for the whole splice is measured between A and D.)

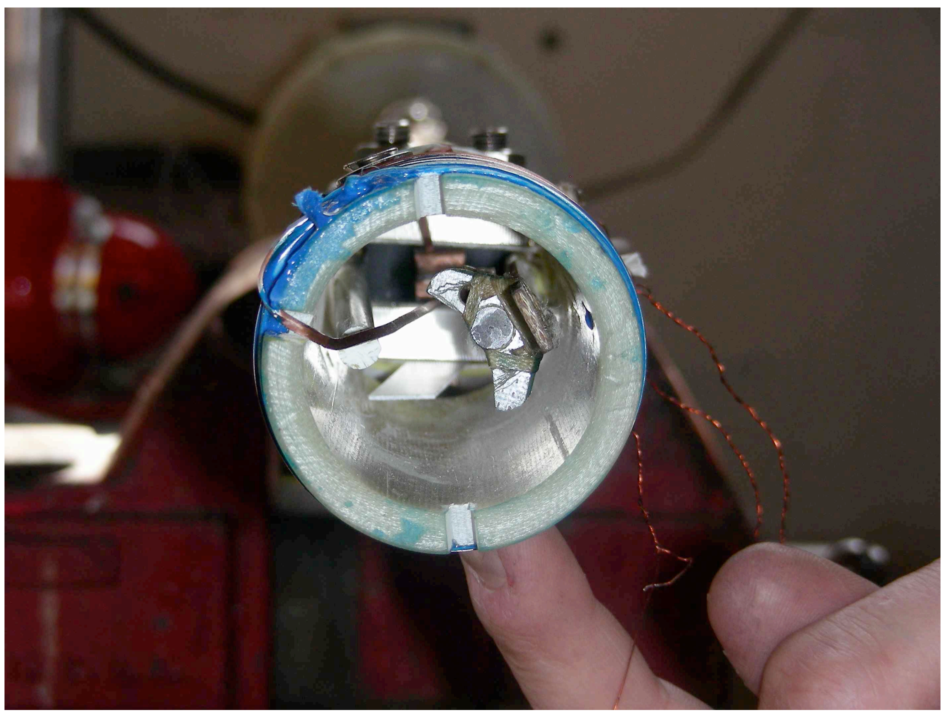


Figure 11. A Splice Mounted on the LBNL Sample Holder as Seen from the End
(One of the current leads is shown inside the sample holder. The fine wires are voltage tap wires.)

The sample carries a current. The voltage drop across the whole splice is measured between voltage taps A and D. When one measures the voltage across the center of the sample (a section that is about 250 mm long), one uses voltage taps B and C. One can also measure the voltage drops from A to C and B to D. Depending on which parts of the samples one measures the sample one can determine which part of the sample is better than other parts of the sample.

A current is I supplied to the sample through gas-cooled that go into the liquid helium. The voltage drop is measured between taps on one conductor in the splice as compared to a voltage tape on the second conductor on the splice. (Taps A to D, A to C, B to C, and B to D) The measured spliced resistance can be calculated by using the following expression;

$$R_j = \frac{abs(V_A - V_D)}{I} \quad \text{-11-}$$

The voltage drop within the center section of the splice is measured between taps B and C. The resistance of the center section of the splice R_{JC} can be calculated by using the following expression;

$$R_{JC} = \frac{abs(V_B - V_C)}{I} \quad \text{-12-}$$

When one compares the performance of one sample with another sample or from one part of the sample to another part of the sample, the data must be normalized. The normalized length should be for a splice that is 1-meter long. The normalized joint resistance R_{JN} can be calculated for the whole splice and the normalized resistance the center section of the splice R_{JNC} using the following expressions;

$$R_{JN} = \frac{abs(V_A - V_D)L}{I} \quad \text{-13-}$$

and

$$R_{JNC} = \frac{abs(V_B - V_C)L}{IL_{B-C}} \quad \text{-14-}$$

where I is the test current; L is the length of the splice; and $L_{B\text{-}C}$ is the length between voltage taps B and C. For the samples that have been tested by LBL, the length $L_{B\text{-}C}$ is about 250 mm.

If one wants to look at the performance of the sample at the ends alone, one must know the length of the splice between end A and the center section at point B $L_{EA\text{-}B}$ and the length of the splice between end D and the center section at point C $L_{ED\text{-}C}$. The following expressions can be used calculate the performance of the splice ends:

$$R_{JN(EA-B)} = \frac{\{abs(V_A - V_C) - abs(V_B - V_C)\}L}{IL_{EA-B}} \quad \text{-15-}$$

and

$$R_{JN(EC-D)} = \frac{\{abs(V_B - V_D) - abs(V_B - V_C)\}L}{IL_{EC-D}} \quad \text{-16-}$$

It may be of interest to look at the normalized resistance of the ends of the joints, if the normalized joint resistance for the center of a joint is significantly different from the normalized resistance of the whole joint. It is desirable that the normalized resistance of the whole joint between two conductors be no more than thirty percent different from the normalized resistance of the central portion of the joint.

Measured Joint Resistance Compared with Calculated Joint Resistance

Figure 12 shows the basic data for the first ICST splice measured at LBNL at 4.2 K in a magnetic induction of zero. Figure 12 shows the voltage of one voltage tap with respect to a second voltage tap. The maroon squares show the voltage of voltage tap A with respect to voltage tap D as a function of the current in the 1.02-meter long splice as a function of the current through the sample. The blue diamonds show the voltage of tap B with respect to the voltage of tap C (for the 0.25-meter center section of a 1.02-meter long splice) as a function of the current in the splice.

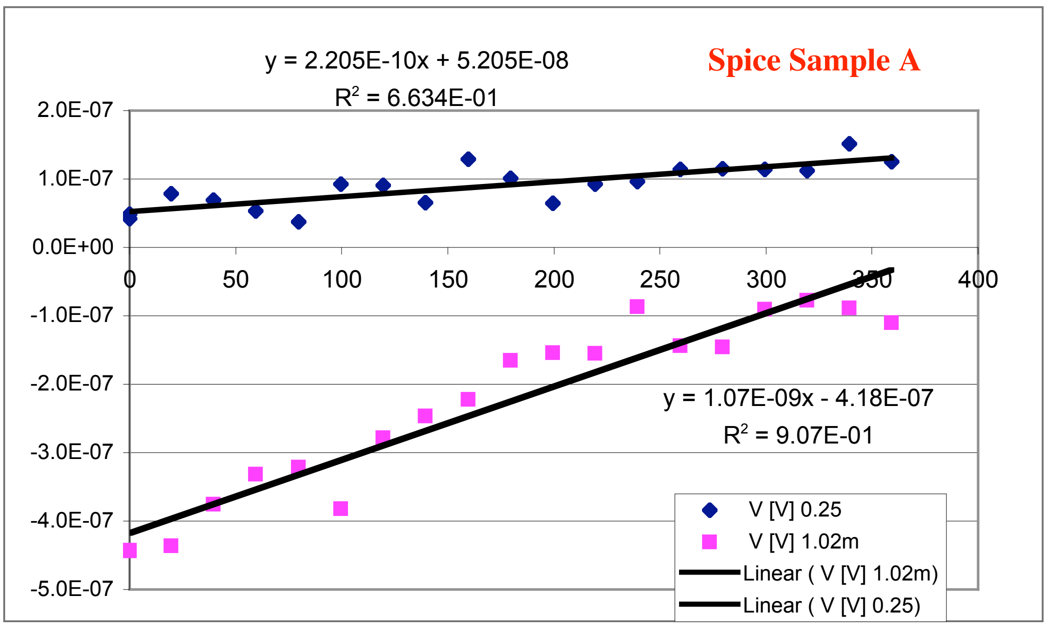


Figure 12. Raw Voltage Drop versus Current Test Data for the First Up-down ICST Splice measured at LBNL (Type of Solder 96Sn-3.5Ag-0.5Cu; L =1.02m, $L_{B\text{-}C}$ = 0.25 m; and B = 1T.)

Using Equation 11, one calculates an overall resistance of splice R_J = 1.06 nΩ. Using Equation 12, one calculates the effective resistance of the splice center R_{JC} = 0.212 nΩ. When one looks at the normalized resistance for the whole joint R_{JN} and the normalized resistance of the splice center R_{JNC}, one finds that R_{JN} = 1.081 nΩ, and R_{JNC} = 0.859 nΩ. Since the center section normalized resistance is nearly the same of the total splice normalized resistance, the splice appears to be a well made. The solder thickness within the splice is not known.

It is useful to look at the normalized resistance of the all of the splices tested at LBNL. From these tests, one can determine the effect of the splice overall length and the effect of the solder resistivity. By comparing the normalized resistance of the splice center with respect to the splice as a whole, one can determine whether the quality varies along its length. The properties of the ICST splices are shown in Table 4. The overall splice resistance at B = 1 T (R_J), the normalized splice resistance at B = 1 T (R_{JN}), and the normalized splice resistance of the center section at B = 1 T (R_{JNC}) for ICST splices shown in Table 4 is summarized in Table 5.

Table 4. The Properties of the ICST Splices Measured at LBNL

Splice	Splice Type	Type of Solder	Splice Length	B to C Length
A	Up-Down	Sn-Ag	1.02 m	0.25 m
B	Side-by-Side	Sn-Ag	1.00 m	0.25 m
C	Up-Down	Sn-Pb	1.04 m	0.25 m
D	Side-by-Side	Sn-Pb	1.00 m	0.25 m

Table 5. The Measured Splice Resistance R_J (see Eq 11), Center Section Resistance R_{JC} (see Eq. 12), and the Normalized Splice Resistances R_{JN} (See Eq. 13) and R_{JCN} (See Eq. 14) at B = 1 T for the Splices shown in Table 4

Splice	Splice Resistances (nΩ)			
	R_J	R_{JC}	R_{JN}	R_{JCN}
A	1.06	0.212	1.08	0.86
B	1.17	0.285	1.17	1.14
C	1.20	0.207	1.25	0.86
D	1.54	0.835	1.54	3.34

The splices in Tables 4 and 5 all have normalized resistances (for 1-meter long splices) from 1.08 to 1.54 nΩ at a magnetic induction of 1 T. Spice D a side-by-side splice made with tin lead eutectic solder (Sn63-Pb37) has a large variation between the center section and the ends. This suggests that there may be quality control problems with this splice, because a large amount of the voltage drop seems to be taken in the center section of the splice. From the data shown in Table 5, one cannot make a strong case for either type of solder. When looks at the data casually, one can make a slight case in favor of the tin-silver solder. There is less variation in the normalized resistance of the center section compared to the joint as a whole. The selection of the solder may be made based on other criteria. One should ask the following questions about the two types of solder: 1) Are the joints made with one type of solder significantly stronger than joints made with the other type of solder? 2) Is the resistance of the splice significantly different at higher field for one type of solder compared to the other?

The issue of joint strength is an important one. First the joint are wound under considerable tension at room temperature (up 135 N). Much of this tension remains after the magnet is cooled down. The tension increases as the magnet is charged. Pure tin changes phase as it is cooled to cryogenic temperatures. This contributes to tin rot (a weakening of the tin due to change of phase). Alloying the tin with lead or silver certainly makes the solder stronger. Tensile stress and strain measurements should be made with the superconductor splices with the cross-section stressed to a least 160 MPa (the yield stress of the conductor when it tentioned to 240 N) at room temperature and 77 K. It is also useful for a number of 1-meter long splices of each type to be put under tensile stress until either the splice or the conductor breaks. If there is a significant difference in the strength of the splices, the stronger splice at 77 K should be used.

The normalized resistance of the two side-by-side joints (one joint with each solder type) is plotted as a function of magnetic induction in Figure 13. The normalized resistance of the two up-down joints (one joint of each solder type) is plotted as a function of magnetic induction in Figure 14. The plot points in Figures 13 and 14 are for the full-length joints and the 0.25-meter long center sections of the joints. The center section normalized resistance as a function of magnetic induction may be different from the normalized resistance for the joint as a whole.

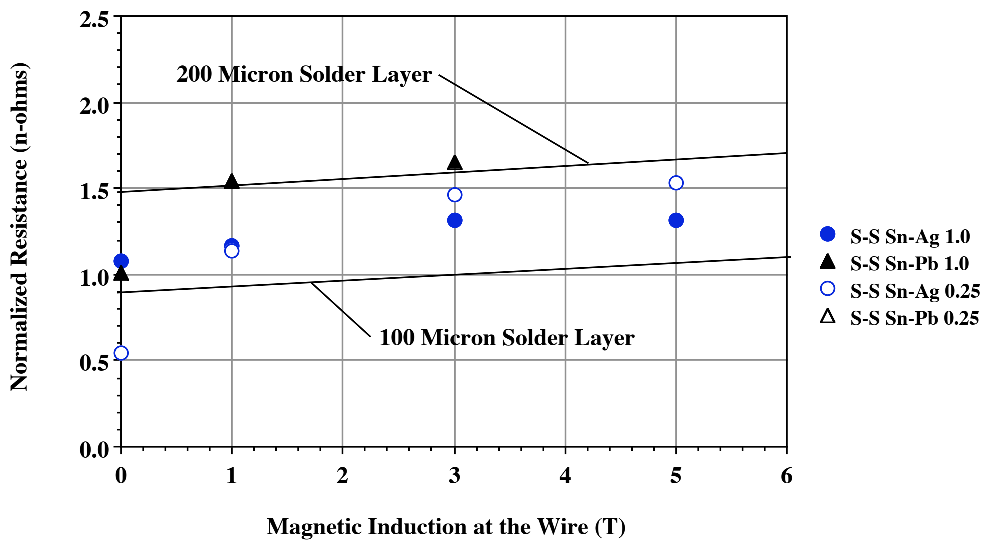


Figure 13. Normalized Side by Side Splice Resistance and a Function of Magnetic Induction For the Full length (~1.0 m) Splice and the Splice Center (0.25 meter) Section

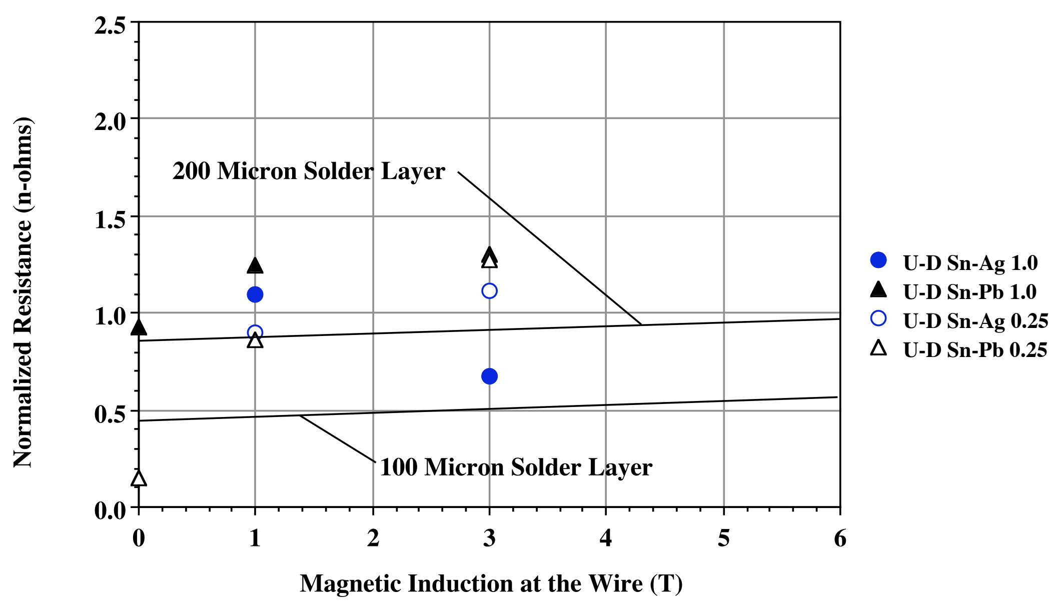


Figure 14. Normalized Up-Down Splice Resistance and a Function of Magnetic Induction For the Full length (~1.0 m) Splice and the Splice Center (0.25 meter) Section

When one compares Figure 13 and Figure 14, one sees that the splice resistance of side-by-side joints is not very different from the resistance of up-down joints. Both types of joints have normalized resistances that are in the range of 0.7 nΩ to 1.7 nΩ. There are some inconsistencies. For example, in Figure 13, the normalized resistance for the center section of side-by-side joints made with eutectic tin lead joints (the open triangle labeled S-S Sn-Pb 0.25) does not even appear on the graph. The normalized resistance for the center section of the joint is greater than 2.5 nΩ yet the joint as a whole has a normalized resistance from 1.0 to 1.7 nΩ. In this particular case, the joint is quite good in the center with a solder thickness that is less than 100 μm, while the rest of the joint is not so good with a thicker layer of solder. There is one joint where the center section normalized resistance is very low in the center section. This is a lead tin joint where a portion of the solder is superconducting at zero field.

The measured up-down joint resistance was larger than expected. Virtually all of the measurements are greater than the theoretical value for solder thickness of 200 μm. This suggests that the solder layers where thicker than expected, or this could also be a sign of solder failure in the joint due to bending. The side-by-side joint resistance lies between the lines for solder thicknesses of 100 μm and 200 μm. There is less likelihood of solder failure, and there is less likelihood for voids to be in the solder. If the joints are strong enough to withstand stresses of 160 MPa, they will be satisfactory for use in the MICE coupling magnets.

In general, the joints are more resistive when they are in a magnetic field. In general, at low fields the resistance increases faster than the theory suggests it should. The resistance does not appear to increase as rapidly at higher fields. The data in Figures 13 and 14 as well as in Table 5 suggest that resistance of the Sn96-Ag3.5-Cu0.5 joints may be lower than for the Sn63-Pb37 joints (lead tin eutectic joints). There may be a couple of reasons for this; 1) Tin-silver solder may flow better between the conductor, so the average thickness of the solder is lower. 2) The tin-silver solder may have a lower overall resistivity. The difference in joint performance seems more pronounced for joints. The difference between the two solders is far less pronounced for the up-down joints. It can be argued that the differences seen in Table 5 and Figures 13 and 14 are within the error band for the measurements. Since all of the joint measurements are for joints that are satisfactory, the selection of the solder for the joint should be based on other factors besides the joint resistance. The strength of the joint and susceptibility to tin rot at low temperatures are important factors when the joint solder choice is being made.

Measurements of the Joint Breaking Strength

Strength tests were made on the conductor splices were made at ICST in September of 2008. The first of these tests were made on 250 mm long up-down splices made with MICE coupling coil conductor using Sn96-Ag3.5-Cu0.5 solder. This is the solder that ICST prefered to use, because it has no lead in it. LBNL on the other hand is worried about tin rot in splices that are under stress. Tin at low temperatures changes phase, thus tin under stress can turn to powder and lose its strength. From a hazard standpoint, LBNL would prefer to use the lead free solder, provided there is no tin rot in the splice. The splice resistance with the preferred lead-free solder appears to be marginally lower than with the Sn63-Pb37 (the tin-lead eutectic) solder.

Since the room temperature shear stress is the solders used for splices is at least 20 MPa, it is clear that the splices do not have to be very long (less than 25 mm long) to withstand a force that would break the conductor. This can be verified using the simple equation for shear stress that is given as follows:

$$\tau = \frac{F}{wL} \qquad \text{-17-}$$

where τ is the shear stress in the solder. L is the length of the splice, and w is the width of the splice. For up-down splice in MICE conductor with w = 1.6 mm, F = 677 N (minimum breaking force), and τ = 20 MPA, the minimum splice length is about 26 mm. The actual length may be longer because of stress concentrations in the solder joint and incomplete coverage of the solder.

The testing machine for testing splices at room temperature is shown in Figure 15. The machine shown in Figure 15 is similar to the machine used to test the yield and breaking strength of the conductor in 2007. Figure 16 show the machine with the sample in an insulated container that is filled with liquid nitrogen.

Figure 15. The Apparatus for Testing Conductor Splices at 300 K

Figure 16. The Apparatus for Testing Conductor Splices at 77 K

A number 250-mm long splices were tested at 300 K where the strength was expected to be lower. A number of tests using 250-mm long were also done at 77 K, in order to test for the effects of tin rot. None of the 250 mm-long splices tested at room temperature failed within the splice itself. Figure 17 shows the break in a typical room temperature splice. Of the 250-mm long splices tested at 77 K, one splice failed by peeling, but the others failed in the conductor close to the splice. All of the 77 K splices showed some peeling. Figure 18 shows a broken splice tested at 77 K. The splice shown in Figure 18 broke like the splice shown in Figure 17, but there is some peeling of one conductor from the other. It is not clear whether the peeling was due to the test apparatus or due to tin rot in the splice. All of the splices failed at a stress above 450 MPa across a single conductor.

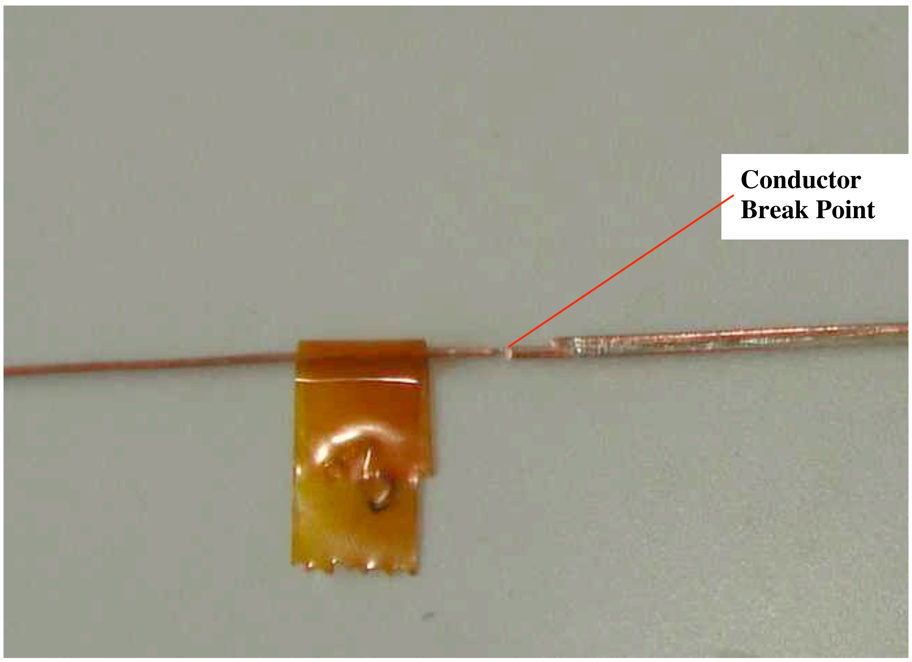


Figure 17. A Conductor Break for a 300 K Conductor Splice Fracture Test
(Note: the clean break in the conductor right next to the conductor splice.)

Figure 18. A Conductor Break for a 77 K Conductor Splice Fracture Test
(Note: The break actually occurred near the pull point, but note there was joint peeling.)

Table 6 shows the measured ultimate stress, yield stress and elongations for the MICE coupling coil conductor that is in tension. The ultimate stress in Table 6 should be compared to the measured breaking stress (across a single conductor) in Table 7 for splices that are from 230 to 270 mm long measured at 300 K and 77 K.

Table 6. The Measured Ultimate Stress, Yield Stress, and Elongation for Coupling Coil Conductor at 300 K

Sample	Ultimate Stress (MPa)	Yield Stress (MPa)	Elongation (percent)
H-1	553	331	3.92
H-2	551	361	1.92
H-3	551	330	5.10
L-1	510	----	----
L-2	522	----	----
L-3	504	371	7.21
L-4	561	360	9.20
L-5*	462	----	----
L-6**	492	----	----
L-7^	502	----	----

* This sample was kinked. The break in the sample occurred at the kink.
** This Sample has the center section at 77 K. The break occurred at the 300 K end.
^ This sample is a 1-meter long up-down splice at 300 K. The splice area is about 2.97 mm^2.

Samples H-1 through H-3 were measured by ICST at HIT. Samples H-1, H-2, and H-3 were made from conductor used in the spectrometer magnet. This conductor is nominally the same as the conductor that is used in the coupling magnet test coils and the coupling magnets themselves. Sample H-2 had been cold worked. The failure of this conductor occurred near the near the cold worked zone. As a result of the cold working, the elongation of this sample was less than samples H-1 and H-3.

Samples L-1 through L-7 measured by LBNL. Samples L-1 through L-6 are from the conductor that will be used in the MICE and MuCOOL coupling coils. Samples L-1 and L-2 were used to calibrate the Instron tensile testing machine at LBNL. The yield stress and elongation was not measured for these samples. Yield stress and elongation were only measured in samples L-3 and L-4. The copper in samples L-1, L-2, L-3, L-4, and L-6 appeared to be softer than samples H-1 through H-3. This might explain why the measured elongation was larger for these samples. LBNL was unable to measure the yield stress and elongation on samples L-5 through L-7. Sample L-5 was a kinked sample that failed at the kink. Sample L-6 was cooled to 77 K in the center over a length of 300 mm. The ends of the sample were at 300 K. Sample L-6 broke at the room temperature end of the sample. Sample L-7 was a one-meter long up down splice made at ICST. Sample L-7 was clamped and wound around the wheels as an up-down soldered conductor.

The yield stress measured on LBL samples L-3 and L-4 was measured for the point when the slope of the strain curve changed. In general, the strain where the slope of the stress strain curve breaks is larger than the nominal 0.2 percent strain that is normally used to determine the yield point for the conductor. The 0.2 percent yield stress is lower than is given in Table 6.

The MICE superconductor is a complex material that is four parts of copper and one part of niobium titanium. The copper is somewhere between the fully annealed state and the fully work hardened state. When the copper is fully annealed it yield stress is about 65 MPa (at 300 K). In the fully hard state, the copper yield stress is 345 MPa (at 300 K) [6]. The ultimate stress for the copper in the annealed state is about 250 MPa (at 300 K). In the fully hard drawn state, the copper ultimate stress is about 360 MPA (at 300 K). The conductor went through a couple of stages of cold working and heat treatment (which anneals the copper). Before the insulation was applied the wire was drawn as a round wire about 1.8 mm in diameter. After insulation, the wire was drawn and sized to its final sized to its final dimensions of 1.0 x 1.65 mm (insulated dimensions). The strain state of the copper in the samples before pulling them is unknown. The niobium titanium yield stress is between 900 and 1100 MPa at room temperature [6]. At 77 K the yield stress for the niobium titanium is about 1600 MPa.

Table 7. Measured Splice Properties, Splice Length, Splice Temperature, and Splice Failure Stress

Sample	**Splice Type**	**Solder Type**	**Splice Length (mm)**	**Splice Temp (K)**	**Failure Stress (MPa)**
HA-1	Up-Down	Sn-Ag	267	300	557
HA-2	Up-Down	Sn-Ag	271	300	536
HA-3	Up-Down	Sn-Ag	270	300	518
HB-1	Up-Down	Sn-Ag	255	77	536
HB-2	Up-Down	Sn-Ag	250	77	538
HB-3	Up-Down	Sn-Ag	251	77	530
LR-1	Up-Down	Sn-Pb	236	300	456
LR-2	Up-Down	Sn-Pb	235	77	516
LR-3	Up-Down	Sn-Pb	230	77	510
LB-1	Up-Down	Sn-Ag	232	300	474
LB-2	Up-Down	Sn-Ag	238	77	522
LB-3	Up-Down	Sn-Ag	233	77	510

Table 7 shows the measured strength of the splices at 300 K and 77 K. The samples that start with an H were measured by HIT. The L samples were measured by LBL. Splices HA-1 through HA-3 and HB-1 through HB-3 were made using the spectrometer solenoid conductor. The conductor used to make the LR and LB splices is not known, but there is a good chance that this conductor comes from the rolls of coupling coil conductor. Since the coupling magnet conductor has a lower ultimate stress (on average) than the spectrometer magnet conductor, this is an explanation for the lower ultimate stress for the LBL measured samples.

Most of the conductors broke close to the splice or at the pull point, because there was a stress concentration in the conductor where the break occurred. The splices that were at 77 K all broke at the room temperature end. In all cases, the conductor broke in single conductor sections. The breaks occurred over a range of conductor forces from 677 N to 827 N. The conductor cross-section area without deformation was 1.485 mm^2. At room temperature, the range of breaking forces is from 677 N to 827 N. For the splices at 77 K, the range of breaking forces was narrower from 757 N to 799 N. The break in the 77 K splices always occurred at the room temperature part of the sample (away from the splice).

At the point where the breaks actually occurred there was some reduction of the conductor cross-sectional area. The breaking force equates to a conductor average stress across the single conductor in a range from 456 MPa to 557 MPa. The 77 K sample breaking stress appeared to be in the same range as the room temperature samples. The yield stress within the conductor at room temperature is from 331 to 371 MPa (see Table 6). The maximum winding stress for the conductor is about 160 MPa (less than 50 percent of the yield stress). The projected winding stress for the MICE coupling coils is from 70 MPa to 110 MPa.

None of the room temperature splices exhibited any peeling when they were stressed to the breaking point in tension. At room temperature, the Sn96-Ag3.5-Cu0.5 solder and the Sn63-Pb37 solder behaved the same. At 77 K all of the Sn96-Ag3.5-Cu0.5 splices exhibited peeling. The measured peel lengths were as large as 100 mm. At 77 K, one splice made with Sn63-Pb37 peeled about 7 mm at one end. The second Sn63-Pb37 splice at 77 K exhibited no peeling. There appears to be more peeling in the Sn96-Ag3.5-Cu05 splices at 77 K than in the Sn63-Pb37 splices. The number of Sn63-Pb37 splices at 77 K is not large, so it is not clear whether the conclusion is correct.

There are several possible explanations for the peeling observed during the 77 K tests. They are: 1) The joint section that is stressed the most is under the solder, causing the solder to fail in shear. 2) The ductility of the solder is lower at low temperature. 3) Tin rot occurs in the very high tin solder that is 96 percent tin. In all cases where peel occurred, the break occurred well away from the peel zone, so it is unlikely that cause 1 is the culprit. Causes 2 and 3 are related to each other. Soft solders are less ductile at low temperature. The Sn96-Ag3.5-Cu0.5 solder is less ductile than the tin-lead solders. Tin rot is caused by a change of phase in the tin when it is cooled to low temperature. It is not clear whether the Sn96-Ag3.5-Cu0.5 solder is subject to tin rot. It is known that Sn50-Pb50 and Sn63-Pb37 solders are not subject to tin rot. Many superconducting magnet groups use lead-tin solders despite the fact that these solder may be a hazard because the solder contains lead.

Since the splices were taken to failure and broken, it is not known how the splices will behave under continuous stress cycling above the yield stress for the conductor. The following is recommended: 1) The maximum stress in the conductor should be less than 165 MPa (about 55 percent of the 0.2 percent yield stress of the conductor). 2) A solder such as Sn63-Pb37 should be used to fabricate the splices in the MICE magnet coils despite the fact the solder contains lead.

More tests need to be done to see how short the splices (less than 50 mm) fail by shear failure in the splice. Since none of the room temperature samples tested failed in the joint, it is useful to see when actual splice shear stress failure in the solder occurs. This information is useful for determining the parameters for the joints between the MICE conductor and the HTS leads. Further tests are needed using splices from 10 mm to 150 mm long. Both types of solder should be used for the tests, and the splices should be tested at 77 K and 300 K.

Some Concluding Comments

One can calculate the projected resistance of splices between rectangular conductors. Butt splices were considered, but their resistance is much higher that lap splices. A butt splice for a conductor with dimensions of 0.95 by 1.60 mm will have a resistance of 100 nano-ohms unless the superconducting filaments are bonded together in the process of making the splice. Conductors with 50 filaments can be bonded so that they are persistent at low fields. It is unlikely that a splice using the MICE magnet conductor would ever be persistent.

Lap splices were calculated for round conductors and rectangular conductors. The theoretical splice resistance for a round conductor with the same area as the rectangular conductor is two to six times the splice resistance of the splices between the rectangular conductors. Up-down splices have a lower resistance than side-by-side splices for the same conductor. Splices between conductors with rounded corners have a higher resistance than splices between conductors without rounded corners. The resistance of the splice is inversely proportional to its length. Splice resistance has two components, the copper resistance and the solder resistance. The resistance of both components increases with magnetic field. For the conductors used in the MICE and MuCOOL magnets, the solder resistance is higher than the copper resistance because the copper has an RRR = 70. The thickness of the solder is an important factor in determining the splice resistance.

The resistance of four 1-meter long splices was measured at the Lawrence Berkeley Laboratory by the LBNL Supercon group. Two up-down splices were measured, and two side-by-side splices were measured. Two of the splices used Sn96-Ag3.5-Cu0.5 (the tin silver solder), and two of the splices used Sn63-Pb37 (the tin lead solder). Thus there was one measurement of each splice type with each solder type. The actual length of the splice varies from 1.00 meters to 1.04 meters. For comparison the splice resistance was normalized to that of a one-meter long splice. The splices were measured in a magnetic field that varied from zero to 5 T. The measured resistance was higher than the theoretical resistance for a splice with 100 microns of solder. In most cases the measured splice resistance was lower than the theoretical resistance with 200 microns of solder. The measured tin silver solder splice resistance appeared to be a little lower than the measured tin lead solders splices. The differences between the two solders appear not to be very significant. There are large error bars in the measurements as is illustrated in Figure 12.

The yield and ultimate tensile stress was measured for the spectrometer magnet conductor and the conductor for the coupling magnets. In general, the coupling magnet conductor is not quite as strong as the spectrometer conductor. The elongation is higher for the coupling magnet conductor than the spectrometer conductor because the copper appears to be a little softer. The conductor yield stress is in the range from 331 MPa to 371 MPa; the ultimate stress was in the range from 462 MPa to 561 MPa. The breaking stress was measured for splices that range in length from 230 mm to 271 mm. The splices were at 300 K and 77 K. The splices themselves did not break. All breaks occurred in the conductor that went into the splice. Many of the 300 K splices broke very close to the splice. In no case did the 300 K splices peel during the test. All of the 77 K splices broke in the room temperature part of the conductor that attached to the pulling machine. All of the 77 K splices for the tin-silver solder exhibited some peel. Of the two 77 K splices made with the tin-lead solder, one peeled about 7 mm. The other 77 K tin-lead splice exhibited no peeling. The tin-lead solder appears to be more ductile than the tin silver solder. As a result, the tin-lead solder should be preferable despite it higher resistance.

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